Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics

Jorge Álvaro-Fuentes [a,*], Francisco Joaquín Morell [b], Daniel Plaza-Bonilla[b], José Luis Arrúe [a], Carlos Cantero-Martínez [b]

[a] Departamento de Suelo y Agua. Estación Experimental de Aula Dei. Consejo Superior de Investigaciones Científicas (EEAD-CSIC). P.O. Box 13034, 50080, Zaragoza, Spain.

[b] Departamento de Producción Vegetal y Ciencia Forestal (Unidad Asociada EEAD-CSIC), Universidad de Lleida, Avda. Rovira Roure 191, 28198 Lleida, Spain.

* Corresponding author. Tel.: +34-976-71-6123 ; fax: +34-(976)-716145

E-mail address: jorgeaf@eead.csic.es

Abstract

Agricultural management plays an important role in global warming mitigation due to its effects on soil organic carbon (SOC) dynamics. In Mediterranean agroecosystems, the interactive effects of tillage and N fertilization on SOC storage have scarcely been studied. Hence, we here present a modelling study in which the effects of both tillage and N fertilization on SOC dynamics are investigated. We used SOC and C input data from a long-term (13 years) field study located in northeast Spain, firstly to validate both the Century model and the Rothamsted Carbon (RothC) model and secondly to predict future SOC dynamics until the year 2030. Tillage and N fertilization affected SOC stocks in the 0-30 cm soil layer. However, the interaction of the two factors was not significant. Averaged over the three N fertilization rates, the observed mean SOC stocks in conventional tillage (CT) and no-tillage (NT) were 29.8 and 36.8 Mg C ha^{-1}, respectively. In addition, the observed SOC stocks, averaged for both tillage systems, increased with increasing N rates, with 30.6, 33.5 and 35.8 Mg C ha^{-1} for the 0, 60 and 120 kg N ha^{-1} rates, respectively. In general, both the Century model and the RothC model performed well in predicting SOC dynamics. Model predictions showed that in Mediterranean dryland agroecosystems SOC dynamics in the next 20 years would be variable according to the tillage and N fertilization applied. According to these predictions, scenarios with NT and high fertilization rates (e.g., 60-120 kg N ha^{-1}) could lead to significant SOC sequestration and associated CO_2 emission offsetting. However, these scenarios with high SOC sequestration rates also showed high mineral N accumulation in the soil profile with its associated environmental side effects.

Keywords: Soil organic carbon modelling; Tillage; Nitrogen fertilization; Semiarid agroecosystems

1. Introduction

Agricultural management plays an important role in global warming mitigation due to its effects on soil organic carbon (SOC) dynamics. According to estimates in the literature, the amount of SOC in the 0-30 cm soil layer is about twice the amount of carbon (C) in atmospheric carbon dioxide (CO_2) (Powlson et al., 2011). In agricultural systems, changes in management can result in increases in the SOC stocks. In addition, enhancing SOC levels also contributes positively to crop production through improvements in fertility and soil and water conservation (Álvaro-Fuentes et al., 2008a; Johnston et al., 2009).

The impact of agricultural management on SOC has been extensively reviewed (e.g., Paustian et al., 1997; Morgan et al., 2010). Management practices such as no-tillage (NT) have been frequently recognized for their effect on SOC storage (Lal and Kimble, 1997). Observations in different parts of the world have reported significant SOC increases in NT compared to conventional tillage (CT) (e.g., Halvorson et al., 2002a; Maia et al., 2010), particularly in topsoil layers (Angers and Eriksen-Hamel, 2008). However, in the case of other management practices such as nitrogen (N) fertilization the effects on SOC storage are not as clear (Alvarez, 2005; Khan et al., 2007).

In Mediterranean conditions, the effects of tillage on SOC dynamics have been reported in several long-term experiments established in the last two decades (see data compilation by Álvaro-Fuentes and Cantero-Martínez, 2010). As shown by other studies worldwide, in Mediterranean conditions adoption of NT has led to SOC sequestration rates ranging from 0.40 to 0.50 Mg C ha^{-1} yr^{-1} (Mrabet et al., 2001; Álvaro-Fuentes et al., 2009; Hernanz et al., 2009). However, in Mediterranean agroecosystems, the effects of N fertilization on SOC accumulation have been less extensively investigated though several studies in the area have reported positive effects of N fertilization on crop production (e.g., Cantero-Martínez et al., 2003; Ryan et al., 2009). Moreover, in some Mediterranean areas, mineral N has been applied more than needed, as observed in recent decades in northeast Spain (Angás et al., 2006).

Long-term experiments are essential to determine the impact of agricultural management on SOC accumulation. However, a major limitation of the information reported by these experiments is the impossibility of determining future trends in SOC dynamics. In recent decades, the development of soil organic matter (SOM) models has helped us to understand the factors affecting SOC dynamics in the long-term and thus increased our ability to predict future SOC trends (Parton et al., 1996; Molina and Smith, 1997). The Century biogeochemical model (Parton et al., 1994) and the Rothamsted Carbon (RothC) model (Coleman and Jenkinson, 1996) have been widely used to simulate SOC changes under different management conditions in long-term experiments (e.g., Kelly et al., 1997; Coleman et al., 1997).

In Mediterranean conditions, even though SOM models have already been used to predict SOC changes in agroecosystems (e.g., Jenkinson et al., 1999; Álvaro-Fuentes et al., 2009), the effects of N application on SOC dynamics have not been simulated yet. Accordingly, here we present a modelling study in which the effects of both tillage and N fertilization on SOC dynamics are investigated. We used data from a long-term tillage and N fertilization field experiment located in northeast Spain, firstly to validate both the Century model and the RothC model and secondly to predict future SOC dynamics under different management conditions (i.e., until the year 2030).

2. Materials and Methods

2.1. Site, management and soil and crop C measurements

The experiment was initiated in 1996 in Agramunt, northeast Spain (41º 48'N, 1º 07'E, 330 m). The climate is temperate continental Mediterranean with a mean annual precipitation of 430 mm and a mean air temperature of 13.8 ºC. The soil was classified as Typic Xerofluvent (Soil Survey Staff, 1994), with the following main properties in the Ap horizon (0-28cm) at the start of the experiment: pH (H_2O, 1:2.5): 8.5; electrical conductivity (1:5): 0.15 dS m^{-1}; sand (2000-50 µm), silt (50-2 µm), and clay (<2 µm) content: 465, 417 and 118 g kg^{-1}, respectively; SOC content (0-30 cm): 29.8 Mg C ha^{-1}.

Prior to the beginning of the experiment, the management consisted of rainfed barley continuously cropped, with intensive tillage, high N applications (between 100-150 kg N ha^{-1}) and straw removal from the field. In 1996, two tillage treatments (CT and NT) with three N fertilization rates (0 kg N ha^{-1} yr^{-1}, 60 kg N ha^{-1} yr^{-1} and 120 kg N ha^{-1} yr^{-1}) were established. The CT treatment consisted of intensive tillage with mouldboard ploughing to a depth of about 25 cm from the soil surface with almost 100% of the residue incorporated into the soil. The mouldboard plough comprised three bottoms of 0.50 m width. The tillage operations were implemented by the end of October or beginning of November. No soil disturbance except for sowing was caused in the NT plots. Rainfed barley was sown in mid-November within two-three weeks of the tillage operations. By the end of June, after the grain harvest, the straw residue was spread over the plot in all the treatments. N fertilizer was split into two applications: one-third of the dose previous to tillage as ammonium sulphate (21% N) and two-thirds of the dose at the beginning of tillering as ammonium nitrate (33.5% N). Tillage and N fertilization were arranged in a randomized block design with three blocks and with a plot size of 50 m x 6 m. Additional details of the experimental site and cropping practices are given in Angás et al. (2006) and Morell et al. (2010). Aboveground crop residue inputs were measured from 1996 to 2009 at maturity (i.e., early June). Four 0.5-m-long rows were hand-harvested per plot. The grain was removed from the plant and the straw was oven-dried for 48 h at 65 ºC and weighed. Belowground crop residue was determined from 2007 to 2009 to 50 cm depth at crop maturity. Roots were separated by washing the soil on a 0.5-mm sieve, and weighed after oven-drying (Morell et al., 2011). We assumed a C concentration of 0.45 in straw for the overall experiment, as obtained by Álvaro-Fuentes et al. (2008b). The SOC content at the beginning of the experiment in 1996 and at the end in 2009 was measured by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982) in two soil samples collected per plot from the 0-30 cm soil layer. The stock of SOC was calculated using soil bulk density values (NT and CT values ranging between 1.33 and 1.67 Mg m^{-3} and between 1.30 and 1.41 Mg m^{-3}, respectively). The SOC sequestration rate was calculated as the difference between the SOC level in 2009 and the initial SOC level in 1996, divided by the number of years between the two sampling dates (i.e., 13 years).

2.2. Description of the SOC models

The temporal SOC dynamics over the 1996-2030 period was simulated using two SOM models: the Century model (version 4.0) and the RothC model (version 26.3). The Century model is a general ecosystem model designed to simulate C, N, S and P dynamics in a monthly time step. The SOM submodel is composed of different pools with different turnover rates. Four of these SOM pools represent surface and soil litter (metabolic and structural) and the other three represent SOM (active, slow and passive). Decomposition rates are functions of first-order rate constants modified by climate (soil temperature and moisture), tillage intensity, soil texture and litter quality (C/N ratio and lignin content). In the plant growth submodel, the maximum plant growth is calculated as a function of the precipitation and reduced if there is insufficient mineral N supply. A detailed description of the model is given in Parton et al. (1987, 1994).

Initialization of the SOM pools was done in two parts. In the first part, the most recalcitrant pool was initialized simulating an equilibrium period for 5000 years using the same parameterization as previously used for a similar study also located in NE Spain (Álvaro-Fuentes et al., 2009). In the second part of the initialization process, and in order to initialize the slow pool, a period of 100 years previous to the establishment of the experiment was simulated to represent the historical management implemented in the field. Measured site-specific parameters such as soil texture, soil bulk density, initial soil C, and soil depth were used to run the model. Moreover, parameter constants controlling crop growth (e.g., harvest index, HIMAX; the effect of water deficit on harvest index, HIWSF and HIMONN; the fraction of N which goes to the grain, EFGRN; or potential aboveground production, PRDX) were calibrated to better represent crop growth according to the values measured during the experimental period. Non-site-specific parameters that control C flow and decomposition among different SOM pools were changed following the procedure of Metherell et al. (1993) to allow the model to simulate SOC dynamics in the 0-30 cm soil depth. Originally, the Century model was calibrated to simulate SOC in the 0-20 cm soil layer. However, since tillage in our study was implemented up to 25 cm depth, we considered it more useful to simulate SOC dynamics up to 30 cm depth in order to predict possible C accrual in deeper layers in the CT treatments (Angers and Eriksen-Hamel, 2008).

The RothC model includes five SOM pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (Cmic), humified organic matter (HUM) and inert organic matter (IOM). The clay content determines the C flow from plant material C to Cmic+HUM or C lost to the system (as CO_2). As in the Century model, decomposition rates are functions of first-order rate constants modified by soil moisture, temperature and plant cover. Data requirements for the RothC model were: the monthly open pan evaporation, the monthly mean air temperature, the monthly precipitation, the soil depth, the clay content, the DPM/RPM ratio for the crops, the soil cover, the monthly input of plant residues and the amount of IOM. A DPM/RPM ratio of 1.44 was used as suggested by Coleman and Jenkinson (1996). The amount of IOM was estimated from the equation given by Falloon et al. (1998), which estimates the IOM from the SOC content. A more detailed description of the RothC model is given in Coleman and Jenkinson (1996).

Contrary to the Century model, the RothC model is not able to simulate crop growth and thus C inputs were given to the model. For initialization purposes, the model was run iteratively with different annual inputs of plant C until the measured SOC content in the 0-30 cm layer in 1996 was reached (Coleman and Jenkinson, 1996). For the simulation of the experimental period with the RothC model, observed C inputs from the long-term experiment were used.

2.3. Statistical analyses

Measured SOC stocks in 2009 were statistically tested with analyses of variance considering tillage, N fertilization level and their interactions. For the N fertilization factor, differences among N rates were tested with an LSD test at P=0.05. The performance of the models was evaluated using the root mean square error (RMSE) and the model efficiency (EF) (Smith et al., 1996):

$$RMSE = \frac{100}{\bar{O}} \sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n} \qquad (1)$$

$$EF = \frac{\left(\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2\right)}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \qquad (2)$$

where $\bar{O}$ are the mean of the observed values, O_i are the observed values, Pi are the predicted values, and n is the number of paired values.

The RMSE statistic can be used to compare the error of different models. A lower RMSE indicates a lower difference between the observed and simulated values. The EF statistic provides an estimation of the accuracy of the simulations. An EF value of 1 indicates a perfect match between the predicted and observed values (Smith et al., 1996).

3. Results and discussion

3.1. Observed SOC stocks as affected by tillage and N fertilization rates

After 13 years of experiment, tillage and N fertilization affected SOC stocks in the 0-30 cm soil layer (Table 1). Averaged over the three N fertilization rates, the mean SOC stocks under CT and NT were 29.8 and 36.8 Mg C ha^{-1}, respectively (Table 2).

Furthermore, the SOC stock in the CT treatment was maintained similar to the initial SOC content measured in 1996 (i.e., 29.8 Mg C ha^{-1}). However, under NT it increased at a rate of 0.53 Mg C ha^{-1} yr^{-1} (Table 2). Under Mediterranean conditions, SOC gains after cessation of tillage have been widely demonstrated (e.g., Mrabet et al., 2001; Álvaro-Fuentes et al., 2008c; Hernanz et al., 2009). Among other effects, the adoption of NT slows soil aggregate turnover, decreases soil aeration and reduces the incorporation of plant residues in the soil (Paustian et al., 1997; Six et al., 1999). Consequently, these processes stimulate SOC build-up when tillage is ceased.

The SOC content is a balance between C inputs and C losses. In the conditions under study, NT adoption not only results in lower SOC losses but also in greater C inputs. Table 3 shows the observed aboveground C inputs averaged over the whole study period (i.e., 1997-2009). Comparing tillage systems, aboveground C inputs were 30% greater under NT than under CT (i.e., 1.86 vs. 1.43 Mg C ha^{-1}, respectively) (Table 3). Since in both tillage systems the entire crop residues were left on the soil surface, differences in C inputs were explained by differences in crop productivity between tillage systems. In Mediterranean Spain, Cantero-Martínez et al. (2007) studied the effects of tillage systems on crop production in three long-term experiments located along a precipitation gradient. They observed that NT was more effective in increasing crop production, particularly at the driest site, where higher water-use efficiency was observed in NT compared to CT. In the same study area, Lampurlanés et al. (2002), studying soil water storage under different tillage systems, concluded that the increased crop residue left on the soil surface in NT compared to CT leads to more water being stored in the soil and thus to higher biomass production.

Averaged for the two tillage systems, SOC stocks increased with increasing N rates, with 30.6, 33.5 and 35.8 Mg C ha^{-1} for the 0, 60 and 120 kg N ha^{-1} rates, respectively

(Table 2). However, when analysed for each tillage treatment, no differences in SOC stocks among N rates were obtained in the CT treatment. By contrast, differences between the 0 and 120 kg N ha^{-1} rates were obtained in NT (Table 2). The effect of N on SOC sequestration is still a question in debate (Reid, 2008). Alvarez (2005) reviewed the effects of N on SOC sequestration, compiling published data from more than one hundred sites around the world. This review showed the disparity in the responses of SOC to N fertilization. Two significant conclusions of this study were that the response of SOC to N fertilization was site-specific and also that the increase in C inputs due to higher N rates resulted in SOC storage (Alvarez, 2005). However, some studies have reported zero effects of N applications on SOC, even measuring increases in C inputs (Halvorson et al., 2002b; Poirier et al., 2009). In our study, N rates only affected C inputs in the NT treatment in which the application of 120 kg N ha^{-1} increased C inputs almost 70% compared to 0 kg N ha^{-1} (Table 3). This difference in C inputs was similar to the difference in SOC stocks obtained between fertilized and unfertilized plots (Table 2). In Mediterranean dryland conditions, some experiments have demonstrated that crops respond to N fertilization as a function of soil water storage (Angás et al., 2006; Morell et al., in press). Consequently, lower soil water losses under NT could favour the response of crop growth to N fertilization compared to the treatment CT and thus produce the increase in SOC levels.

3.2. Simulation of the temporal SOC dynamics

For the different tillage and N fertilization rates, the simulation of the SOC dynamics from the beginning of the experiment until the year 2030 using the Century and the RothC models is shown in Figures 1 and 2. It is worth mentioning that the simulations of the future (i.e., 2009-2030) were made with monthly mean climate data obtained from the 1996-2009 values recorded. Moreover, possible effects of an increase in atmospheric CO_2 on crop growth (Álvaro-Fuentes and Paustian, 2011) were not considered in the simulations, in order to better understand the interactions between mineral N addition and tillage on SOC dynamics, which was the purpose of this experiment.

Conceptually, both models followed an initialization procedure based on the iterative adjustment of the initial SOC value (i.e., 29.8 Mg C ha^{-1}). However, differences in the complexity of the models led to differences in this initialization procedure. Thus, the initialization of the RothC model was done by running the model iteratively for an equilibrium period using different C inputs until the initial observed value was reached. In the Century model, by contrast the iterative procedure entailed the adjustment of several parameters, particularly those related to potential plant production and management effects on SOC. Despite the differences in the procedure used, the initial values predicted by both models were fairly similar to the observed SOC values (Table 4).

Comparison of the different C pools predicted by the two models is difficult since these pools are conceptual pools that do not correspond to measurable SOC fractions (Christensen, 1996). However, some attempts have been made to match measurable SOC fractions with modelled pools (e.g., Sitompul et al., 2000; Skjemstad et al., 2004). These studies have identified some measurable SOC fractions that could be used to relate the initial pools obtained with the Century model and the RothC model. For instance, the RPM pool of RothC could be matched with the som2c of Century since both are related to the measurable particulate organic C (Cambardella and Elliot, 1992). At the outset of the experiment, the RPM and som2c pools predicted by the RothC and the Century models, respectively, were fairly similar (i.e., 4.55 vs. 5.40

Mg C ha^{-1} for RPM and som2c, respectively) (Table 4). Likewise, more recalcitrant pools (i.e., the HUM and som3c pools of the RothC model and the Century model, respectively) could also be matched since both pools have been related to the measured mineral-associated C fraction <53 µm (Skjemstad et al., 2004). In our study, the predicted values obtained for these two pools were also rather similar (i.e., 22.57 vs. 22.16 Mg C ha^{-1} for HUM and som3c, respectively) (Table 4). Consequently, the similarity in the C pools predicted at the beginning of the experiment helped to rule out possible biases in the SOC dynamics predicted by the two models caused by the different initialization of the C pools.

In both tillage treatments, for the unfertilized treatment the models predicted steady SOC stocks over the 34-year period (Figs. 1 and 2). The only exception was the Century model in the CT treatment, which simulated SOC losses over the simulated period (Fig. 1). As mentioned above, the most recent (<30 years) historical management previous to the establishment of the experiment consisted of intensive tillage, high N application and straw removal from the field. Therefore, we could assume a priori that changes in management due to the establishment of the experiment should lead to variations in SOC stocks over the 34-year period, as predicted by the Century model for the unfertilized CT treatment. In particular, the SOC losses predicted by the Century model could correspond to a decrease in the amount of C inputs following the establishment of the experiment.

Throughout the entire experiment, the Century model predicted the C inputs reasonably well, with a significant relationship ($P<0.01$) between observed and simulated values (Fig. 3). However, there were some exceptions such as the slight over-prediction of the C inputs in the CT 60 kg N ha^{-1} treatment as compared to the observed C inputs (Table 3). This could explain the inaccurate prediction of the observed SOC loss in the CT 60 kg N ha^{-1} treatment by the Century model (Fig. 1). For this same treatment, the SOC predicted by the RothC model was also somewhat higher than the observed SOC value. A possible explanation for this difference could be that in the RothC model the C inputs are added as an annual mean for the whole simulation. In dryland Mediterranean agroecosystems, considering the mean C input for the overall simulation could lead to imprecision in the predictions since crop growth is highly variable among seasons due to the inconsistency of the rainfall (Austin et al., 1998).

In the fertilized treatments (i.e., 60 and 120 kg N ha^{-1}) under NT, it is noteworthy the diverse SOC dynamics predicted by the different models (Fig. 2). While the Century model predicted significant increases in the SOC stocks over the entire 34-year simulation period, the RothC simulation showed a steady SOC level from 2009 until the end of the simulation period in 2030 (Fig. 2). The significant increase predicted by the Century model, particularly under the highest N rate (i.e., 120 kg N ha^{-1}), runs counter to other experiments, which have reported decreases in SOC stocks after high N applications due to stimulation of microbial activity (e.g., Green et al., 1995; Khan et al., 2007). Fog (1988) compiled several studies in which decomposition rates decreased with N additions due to biochemical changes driven by excessive N compounds in the soil. Therefore, the considerable increase in SOC stocks predicted by the Century model in NT fertilized plots could be explained by high C inputs due to N additions and also by slower decomposition rates. In the 120 kg N ha^{-1} NT treatment, the Century model predicted slightly greater plant growth in the 2010-2030 period compared to the 1996-2009 period (i.e., average values of 3.36 vs. 3.03 Mg C ha^{-1}, respectively) (Fig. 4). However, during this 20-year period (2010-2030), the model predicted a dramatic increase in the mineral nitrogen accumulated in the soil profile (Fig. 4). It predicted soil mineral nitrogen levels up to 950 kg N ha^{-1}. In the same experimental plots, Morell et al. (in press) measured soil N-NO_3 levels up to 1200 kg N ha^{-1}. These authors attributed such high levels to: (i) the mineral N applied exceeding the crop N uptake; (ii) soil organic matter mineralization; and (iii) the lack of leaching. According to Angás et al. (2006), in the dryland agroecosystems of northeast Spain, water leaching is very low and the rainfall condition for leaching generally occurs only once every 7–10 years.

Moreover, the excessive accumulation of mineral N in the soil profile has concomitant environmental side effects. Although only SOC dynamics has been studied in this experiment, N applications are also associated with N_2O emissions (Bouwman et al., 2002) with their associated impact on global warming. Therefore, even though high N applications under NT could result in significant SOC accumulation, the associated environmental side effect could counteract the atmospheric CO_2 mitigation.

The largest difference in the SOC evolution between the two models was observed in the 120 kg N ha^{-1} NT treatment (Fig. 2). For this treatment, the Century model predicted an almost linear increase in SOC stock without reaching a plateau over the 34-year simulation. However, for the same 120 kg N ha^{-1} NT treatment, the RothC model predicted a plateau in SOC accumulation about 15 years after the establishment of the experiment (Fig. 2). In a global analysis of 93 tillage comparisons, West and Post (2002) estimated a duration of 20 years for SOC sequestration after the adoption of NT. Thus, in this treatment, the temporal SOC dynamics simulated by the RothC model could be more realistic than that simulated by the Century model. Both models used first-order decomposition kinetics. The difference in SOC dynamics between models could be related to the imprecise initialization of the SOM pools of the

Century model. The initialization process can lead to unrealistic SOC dynamics predicted by the model despite it having the same initial SOC value (Basso et al., 2011). Thus, we hypothesized that during the initialization process a slight over-prediction of intermediate labile SOM pools (i.e., slow pool) could result in large increases in SOC after the adoption of NT and the application of 120 kg N ha^{-1}.

3.3. Performance of the models

The Century and RothC models showed a similar low RMSE (i.e., 6.2% and 6.3%, respectively) (Table 5). The modelling efficiency (EF), which compares the efficiency of a chosen model according to the mean of the observations, was also similar and close to 1 in both models (Table 5), which implies that the models are performing effectively (Smith et al., 1996). The performance of the different models was also estimated from regression analyses between the observed and simulated values of SOC (Fig. 5). The relationships obtained by the regression analyses were significant ($P<0.01$) for both models, with coefficients of determination higher than 0.85 (Fig. 5). Therefore, in our experiment the models performed well and were suitable for predicting SOC dynamics under different tillage and N rates.

Model uncertainty can be attributed to the model itself, the initialization of the SOC pools, or the lack of reliable input data (Ogle et al., 2007; Álvaro-Fuentes and Paustian 2011). In this study, for example, even though the Century model predicted C inputs fairly well ($R^2=0.656$; $P<0.01$), some differences existed between predicted and observed values (Fig. 3). Overall, the greatest differences between observed and predicted C inputs occurred in the 0 kg N ha^{-1} treatments (Table 3). Parton et al. (1996) also observed an underestimation of plant production by the Century model at low fertility sites. They attributed this underestimation to the fact that the model does not consider nutrient mineralization at depths below 20 cm in the soil.

A further source of uncertainty could be related to the limited number of observed SOC values used for validation purposes over the 13-year period. After a change in management, the annual SOC sequestration increases during the initial years until it reaches a maximum from which time onwards the annual sequestration decreases (West and Six, 2007). Consequently, increasing the number of observed SOC values during the first few years after the change in management and avoiding the use of SOC sequestration rates for validating purposes could be two valid approaches to reducing uncertainty during the validation process.

4. Conclusions

The results of this study showed that N fertilization and tillage affected SOC stocks. However, the interaction of the two factors was not significant. The NT system led to more C inputs to the soil and thus to greater SOC stocks compared to CT. The effect of N fertilization on SOC varied according to tillage system. Thus, under NT higher N additions resulted in higher C inputs and SOC gains. By contrast, under CT N additions did not affect either C inputs or SOC stocks. As a result, in Mediterranean dryland conditions, the potential ability of N additions to increase SOC stocks is determined by the capability of the soil management system to store soil water.

Our study also showed that SOC models are useful for studying the factors that control SOC dynamics. In general, in the Mediterranean conditions of this study, both the Century model and the Roth C model performed well in predicting SOC dynamics. The only exception was the use of the RothC model with C inputs estimated from the Century model due to the significant uncertainty associated. Model predictions showed that SOC dynamics in the next 20 years would be variable according to the tillage and the N fertilization management applied in Mediterranean dryland agroecosystems. According to these predictions, scenarios with NT and high fertilization rates (e.g., 60-120 kg N ha^{-1}) could lead to significant SOC sequestration with its associated CO_2 emission offsetting. However, these scenarios with elevated SOC sequestration also predicted high mineral N accumulation in the soil profile with its associated environmental side effects.

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Figure captions

Fig. 1. Observed and simulated SOC dynamics in the 0-30 cm soil depth from 1996 to 2030 with the Century model and the RothC model in the conventional tillage (CT) treatment with three N fertilization rates (0N, 0 kg N ha^{-1}; 60N, 60 kg N ha^{-1}; 120N, 120 kg N ha^{-1}). Error bars represent standard error.

Fig. 2. Observed and simulated SOC dynamics in the 0-30 cm soil depth from 1996 to 2030 with the Century model and the RothC model in the no-tillage (NT) treatment with three N fertilization rates (0N, 0 kg N ha^{-1}; 60N, 60 kg N ha^{-1}; 120N, 120 kg N ha^{-1}). Error bars represent standard error.

Fig. 3. Relationship between observed C inputs and C inputs simulated by the Century model.

Fig. 4. Simulated C inputs and mineral N for the no-tillage (NT) and 120 kg N ha^{-1} treatment in the 0-30 cm soil depth according to the Century model during the 1996-2030 period.

Fig. 5. Relationship between observed SOC and SOC simulated by the Century model and the RothC model.

Tables

Table 1. Analysis of variance for SOC stocks (2009) in the 0-30 cm soil depth.

Source of variation	df[‡]	*Pr > F*
Tillage	1	<0.001
N fertilization	2	<0.05
Tillage x N fertilization	2	n.s.

[‡] df: degrees of freedom

Table 2. Observed SOC stocks in 2009 and SOC sequestration rates in the 0-30 cm soil layer as affected by tillage (CT, conventional tillage; NT, no-tillage) and N fertilization rates.

Tillage	N fertilization rate (kg N ha^{-1})	SOC stock (Mg C ha^{-1})	SOC sequestration rate[‡] (Mg C ha^{-1} yr^{-1})
CT	0	28.1	-0.13
	60	29.4B[¶]	-0.03B
	120	31.9B	0.16 B
NT	0	33.2b	0.26b
	60	37.5abA	0.59abA
	120	39.6aA	0.76aA

[‡] Calculated according to an initial SOC stock of 29.8 Mg ha^{-1} measured in 1996.
[¶] Different lowercase letters indicate significant differences between N fertilization rates within tillage treatments ($P < 0.05$). Different uppercase letters indicate significant differences between tillage treatments within N fertilization rates ($P < 0.05$).

Table 3. Mean observed and simulated C inputs by the Century model for different tillage systems (CT, conventional tillage; NT, no-tillage) and N fertilization rates.

Tillage	N fertilization rate (kg N ha^{-1})	Observed C inputs (Mg C ha^{-1})		Simulated C inputs (Mg C ha^{-1})	
		Aboveground[*]	Belowground	Aboveground	Belowground
CT	0	1.30	0.21	1.22	0.32
	60	1.48	0.17	2.35	0.64
	120	1. 53	0.17	2.42	0.67
NT	0	1.39 b[¶]	0.19	0.69	0.18
	60	2.01 aA	0.28	2.03	0.49
	120	2.20 aA	0.32	2.38	0.65

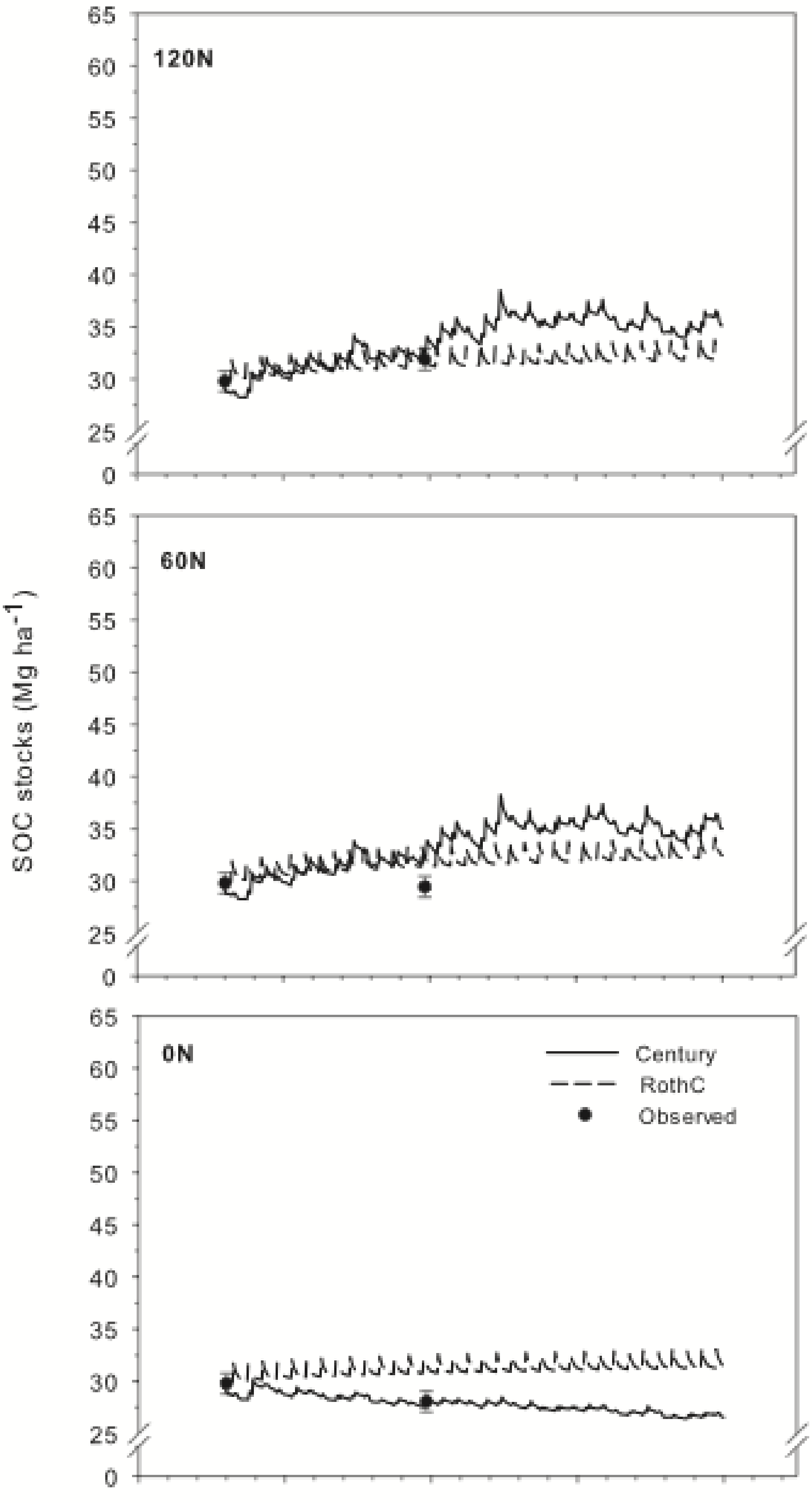
[*] Mean aboveground C inputs during the 1996-2009 period and belowground C inputs during the 2007-2009 period.
[¶] Different lowercase letters indicate significant differences between N fertilization rates within tillage treatments ($P < 0.05$). Different uppercase letters indicate significant differences between tillage treatments within N fertilization rates ($P < 0.05$).

Table 4. Distribution of different SOC pools at the beginning of the experiment (1996) in both the Century ecosystem model and the RothC model.

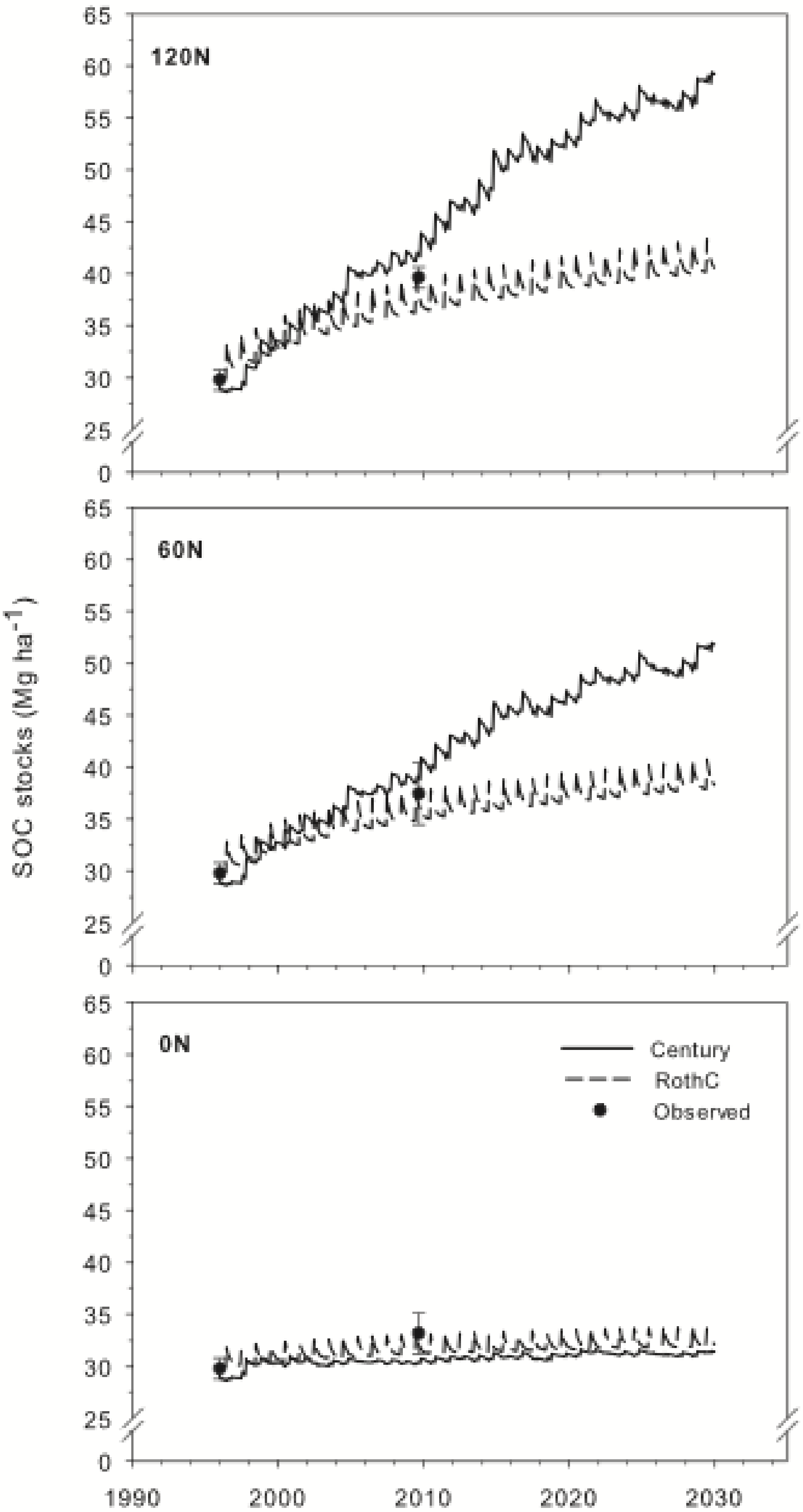
Model	C pool	SOC stock ($Mg\ C\ ha^{-1}$)
Century		
	metabc(2)	0.06
	strucc(2)	0.75
	som1c(1)	0.06
	som1c(2)	0.42
	som2c	5.40
	som3c	22.16
	Total C stock	28.85
RothC		
	DPM	0.02
	RPM	4.55
	Cmic	0.58
	HUM	22.57
	IOM	2.34
	Total C stock	30.06

Table 5. Statistics describing the performance of the models.

Model	*n*	RMSE	EF
Century	6	6.2	0.75
RothC	6	6.3	0.74

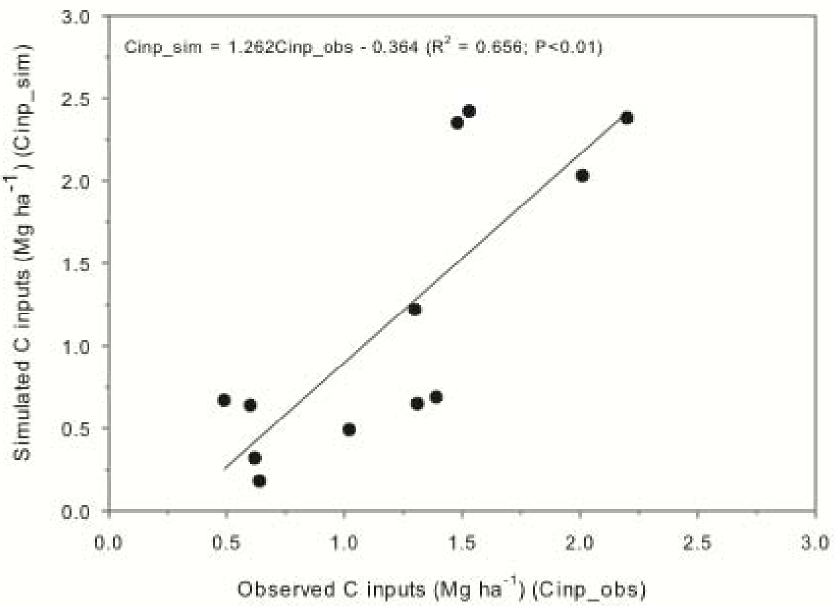

120N
60N
0N
Century
RothC
Observed
SOC stocks (Mg ha-1)
1990
2000
2010
2020
2030

53 Fig. 1



120N
60N
0N
Century
RothC
Observed
SOC stocks (Mg ha^{-1})
65
60
55
50
45
40
35
30
25
0
1990
2000
2010
2020
2030

54 Fig. 2



Cinp_sim = 1.262Cinp_obs - 0.364 (R² = 0.656; P<0.01)
Simulated C inputs (Mg ha⁻¹) (Cinp_sim)
Observed C inputs (Mg ha⁻¹) (Cinp_obs)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Fig. 3

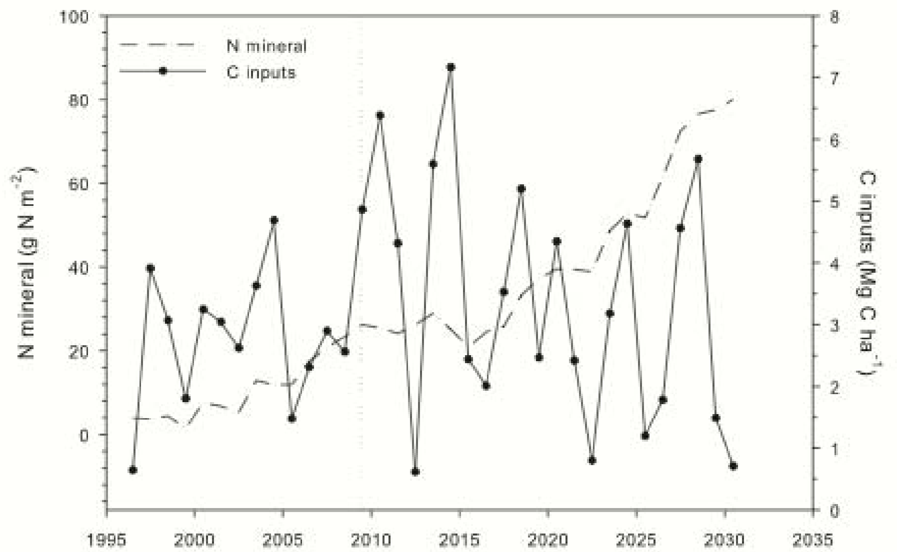

N mineral
C inputs
N mineral (g N m-2)
C inputs (Mg C ha-1)
100
80
60
40
20
0
8
7
6
5
4
3
2
1
0
1995
2000
2005
2010
2015
2020
2025
2030
2035

Fig. 4

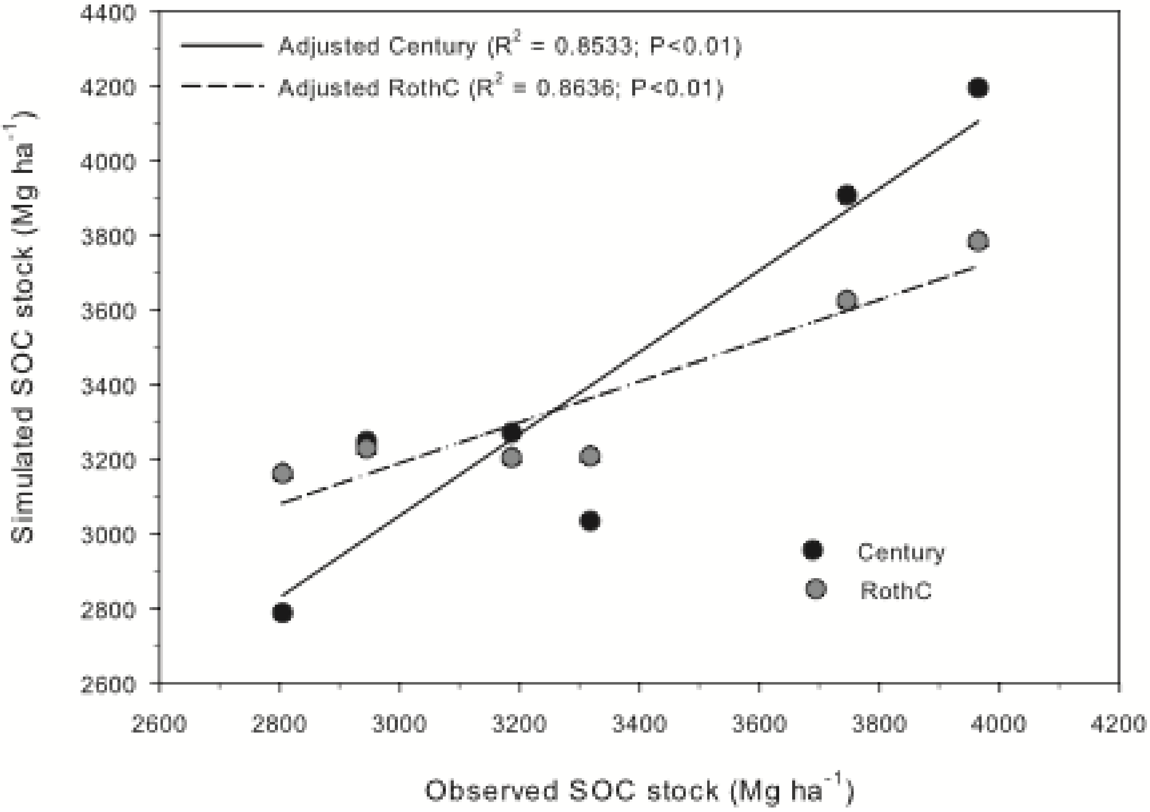

Adjusted Century (R^2 = 0.8533; P<0.01)
Adjusted RothC (R^2 = 0.8636; P<0.01)
Century
RothC
Simulated SOC stock (Mg ha^{-1})
Observed SOC stock (Mg ha^{-1})
4400
4200
4000
3800
3600
3400
3200
3000
2800
2600
2600
2800
3000
3200
3400
3600
3800
4000
4200

Fig. 5